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REVIEW

# Physical and Virtual Laboratories in Science and Engineering Education

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**The world needs young people who are skillful in and enthusiastic about science and who view science as their future career field. Ensuring that we will have such young people requires initiatives that engage students in interesting and motivating science experiences. Today, students can investigate scientific phenomena using the tools, data collection techniques, models, and theories of science in physical laboratories that support interactions with the material world or in virtual laboratories that take advantage of simulations. Here, we review a selection of the literature to contrast the value of physical and virtual investigations and to offer recommendations for combining the two to strengthen science learning.**

Policy-makers worldwide recommend including scientific investigations in courses for students of all ages (*1*, *2*). Research shows advantages for science inquiry learning where students conduct investigations compared with typical instruction featuring lectures or teacher demonstrations (*3*, *4*). Investigations provide opportunities for students to interact directly with the material world using the tools, data collection techniques, models, and theories of science (*1*). Physical, hands-on investigations typically fill this need, but computer technologies now offer virtual laboratories where investigations involve simulated material and apparatus. The value of physical laboratories for science learning is generally recognized (*1*), but the value of virtual, simulated alternatives for hands-on physical laboratories is contested (*5*). We explore whether this hesitation concerning virtual laboratories is justified.

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## Affordances of Physical and Virtual Laboratories

Physical and virtual laboratories can achieve similar objectives, such as exploring the nature of science, developing team work abilities, cultivating interest in science, promoting conceptual understanding, and developing inquiry skills, yet they also have specific affordances (*1*). Using physical equipment, students can develop practical laboratory skills, including troubleshooting of machinery, and can experience the challenges many scientists face when planning experiments that require careful setup of equipment and observations over long time spans. A related affordance of physical laboratories is that they can take advantage of tactile information that, according to theories of embodied cognition, fosters development of conceptual knowledge [see e.g., (*6*, *7*)].

An important affordance of virtual laboratories is that reality can be adapted. Designers of virtual experiments can simplify learning by highlighting salient information and removing confusing details (*8*), or they can modify model characteristics, such as the time scale, that make the interpretation of certain phenomena easier (*9*). Students can conduct experiments about unobservable phenomena, such as chemical reactions, thermodynamics, or electricity (*10*–*13*). For example, students can vary the properties of light rays that travel between a light source and screen (Fig. 1) (*14*, *15*). In virtual laboratories, students can also directly link unobservable processes to symbolic equations and observable phenomena, which encourages them to make abstractions over different representations (*16*–*18*).

Virtual experiments offer efficiencies over physical experiments because they typically require less setup time and provide results of lengthy investigations instantaneously (*19*). This enables students to perform more experiments and thus to gather more information in the same amount of time it would take to do the physical experiment. Physical experiments, however, typically include authentic delays between trials that encourage careful planning and reflection of the next investigation (*20*).

Finally, in physical investigations students learn about the complexities of science by dealing with unanticipated events, such as measurement errors (*21*). In contrast, in virtual laboratories students are not distracted by aberrations in the equipment or unanticipated consequences (*22*). Of course, measurement errors could be modeled in virtual environments, but ensuring that they are authentic would require careful research.

Both physical and virtual investigations succeed when they include worksheets and online and teacher guidance to help students distinguish among their own ideas and the ones demonstrated by the investigation. For example, students benefit when asked to predict the outcome of an experiment and then to compare the result with their own ideas (*4*, *23*, *24*). Similarly, students learn how to extract valid information from a complex visualization when they draw what they observed in an experiment about bond breaking (*12*). For virtual experiments, computer technologies can log student interactions and use the information to diagnose random or uninformative investigations and to prompt students to revise their experimentation strategies and to reflect on their findings (*25*). Teachers can use logs of student work to flag ideas for class discussion, plan their lessons, identify groups of students who need specialized tutoring, and refine their instruction (*4*).

**Empirical Studies Comparing Physical and Virtual Laboratories**

Many well-controlled comparison studies report no differences between physical and virtual laboratories. For example, Wiesner and Lan (*26*), compared virtual and physical equipment for measuring heat exchange, mass transfer, and humidification and found no differences in the performance of chemical engineering students on a test measuring underlying principles. No differences between virtual and physical experiments on tests of conceptual understanding are reported by Klahr *et al*. (*27*) for seventh and eighth graders designing a car or by Zacharia and Constantinou (*10*) for undergraduates learning about heat and temperature. For measures of inquiry skills, Triona and Klahr (*28*) found no difference in virtual and physical experiments for fourth and fifth graders investigating the behavior of springs. These studies illustrate that, for acquiring conceptual knowledge, virtual laboratories can replace physical ones. These studies also suggest that tactile information does not appear to be a requirement for the development of conceptual knowledge or inquiry skills with the exception of students, especially young children, who do not have previous relevant physical experience with the phenomenon or concept under study; for example, Zacharia *et al*. (*7*) found that young children (aged 5 to 6) learning about the working of the balance beam gained more knowledge from physical laboratories than from virtual laboratories.

Many studies show the advantages of virtual, interactive exploration of unobservable phenomena compared with physical experiments of observable phenomena. For example, university students who investigated simulated electric circuits showing moving electrons acquired more conceptual knowledge than those using physical materials (*29*). Similarly, students using virtual optics materials displaying light rays outperformed those using physical materials (*30*). Studies show that virtual experiments can enable students to use complex inquiry practices to separate variables that might be difficult to use in physical experiments (*17*, *27*).

The idea that virtual experiments support the acquisition of conceptual knowledge because they produce clean data is also supported in research. For example, first-year secondary students conducting virtual chemistry experiments outperformed those using a physical laboratory on conceptual understanding, which was partly explained by the messy data produced by the physical lab (*22*).

In the domain of heat and temperature, Zacharia *et al*. (*19*) found that the use of virtual laboratories offered students more time to experience an experiment and to concentrate on its conceptual aspects than the corresponding physical laboratories, because the virtual laboratories allowed faster manipulation of the materials involved in the experiments of the study's curriculum. On the other hand, this ease of experimentation may also lead to less-structured

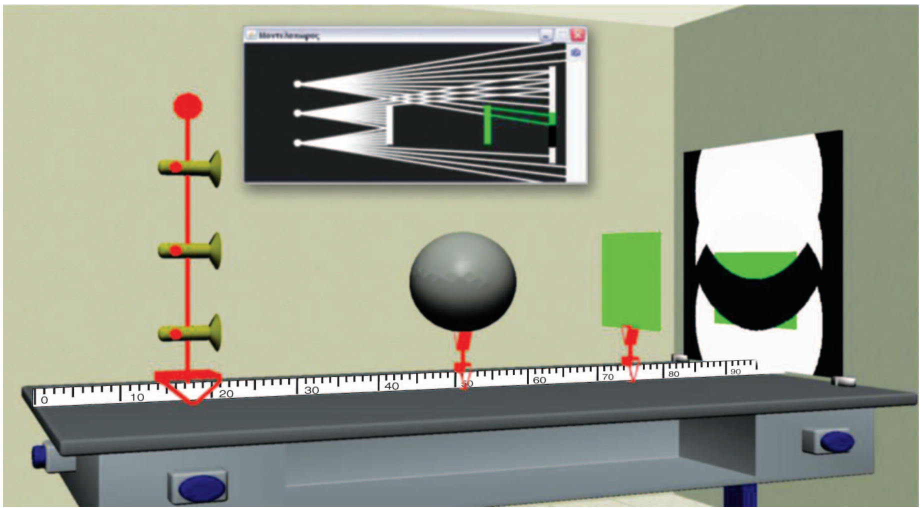

**Fig. 1. OptiLab** (from the AMAP software) illustrates unobservable light rays to help students understand light's behavior (e.g., how the light rays travel, what happens when light rays reach an obstacle or a colored acetate, and the color of the rays involved). In the Optilab environment, students are provided with a virtual workbench on which experiments can be performed, virtual objects (e.g., cubes and metal rings) to compose the experimental setup, virtual materials (e.g., colored light sources, different color filters) whose properties are to be investigated, and virtual instruments (e.g., rulers) and displays (e.g., screen). Students could construct their own virtual experimental arrangements by simple and direct manipulation of virtual objects, materials, and instruments. The software allows lighting up to three light sources at a time; adding as many objects as needed between the light source and the screen; changing the distance between objects, materials, and instruments; and changing the angle that the experimental setup could be observed. The software offers feedback throughout the conduct of the experiment by presenting information (e.g., distance and color) through the displays (the screen and the light ray display) of the software.

investigations by students as recently found, in a situation without guidance for experimentation, by Renken and Nunez (*20*).

These studies show advantages for each type of laboratory, as well as trade-offs. Benefits of virtual laboratories arise when students can investigate unobservable phenomena that are not found in the physical investigation, conduct many more experiments than are possible in the physical setting, link observable and atomic level phenomena, or contrast different depictions of similar phenomena. Physical laboratories have advantages when the instructional goal is to have students acquire a sophisticated epistemology of science, including the ability to make sense of imperfect measurements and to acquire practical skills.

### Combining Physical and Virtual Laboratories

Combinations of physical and virtual experiments can capitalize on the features of each approach. Huppert *et al.* (*31*), for example, found that a group of microbiology students who carried out physical laboratories were less successful on a conceptual test than a group where a simulation was substituted for one laboratory session. Zacharia *et al.* (*19*) found that students conducting a physical laboratory and a virtual laboratory outperformed students doing the physical laboratory on conceptual understanding of heat and temperature. Kolloffel and de Jong (*16*) found that vocational engineering students who did a combination of virtual and physical laboratory were more successful than those doing a physical laboratory alone on both conceptual and procedural knowledge of electric circuits. Climent-Bellido, Martínez-Jiménez *et al.* (*32*) compared chemistry students who used a physical laboratory with students who used a simulation of distillation preceding the physical laboratory and found an advantage for the combination. Olympiou and Zacharia (*30*) studied freshmen students learning about optics under three conditions: only virtual, only physical, and a combination. Students in the combined condition outperformed those in the physical alone and virtual alone conditions, attesting the value of the combination over both other conditions.

Also, Jaakkola *et al.* (*11*) found an advantage for students who conducted physical and virtual experiments over those conducting virtual experiments alone for sixth grade students learning about electric circuits on a measure of conceptual knowledge. Jaakkola *et al.* (*33*) analyzed videotapes of students as they were learning and found that, in the combination condition, students profited from comparing two potentially different representations of the same phenomena and using abstract reasoning to analyze the differences.

Combinations of virtual and physical experiments have succeeded independently of the order of investigation. Toth *et al.* (*21*) studied DNA gel electrophoresis and found a small but nonsignificant advantage for starting with the virtual laboratory and then follow a physical laboratory compared with following the reverse order. Chini *et al.* (*34*) studied conceptual understanding of pulleys and found no differences

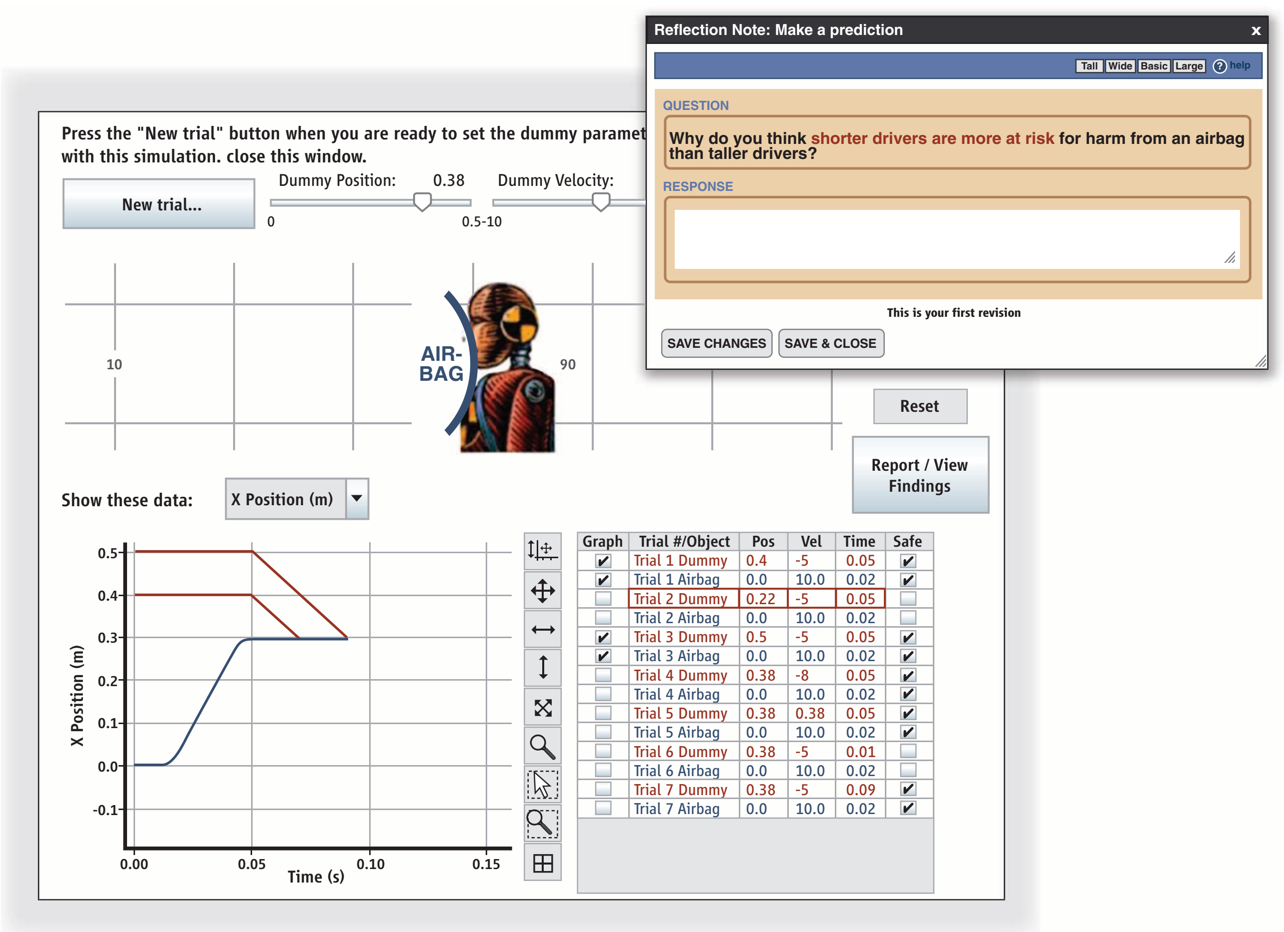


**Fig. 2. Air bags unit.** In the air bags Web-based Inquiry Science Environment (WISE) unit, students conduct virtual experiments to explore a professional laboratory: conditions leading to injuries from an air bag deployed in a car crash. Students make predictions about the variables (such as the driver's height), test their conjectures, interpret graphs of the results, review the record of their experiments, and explain their reasoning. Teachers use online tools to monitor progress of their students, flag student work for discussion, and give online guidance.

**Grand Challenges**

**Create online environments that use stored data from individual students to guide them to virtual experiments appropriate for their stage of understanding.** In this way, online environments can provide students with personalized guidance to maximize outcomes.

**Determine the ideal balance between virtual and physical investigations for courses in different subject areas.** Although the best combination may vary based on circumstances, combining both virtual and physical investigation is likely to be optimal.

**Identify the skills and strategies teachers need to implement a science curriculum featuring virtual and physical laboratories.** The aim is to create a professional development program that enables teachers to revise their lessons based on information obtained from student online work.

between a virtual-physical and a physical-virtual sequence. Overall, well-designed combinations of virtual and physical experiments compared with either one alone allow students to gain a more nuanced understanding of scientific phenomena and a more robust understanding of inquiry.

### Conclusions

Both virtual and physical investigations can meet the goals for investigation in science courses. Both approaches allow students to use tools, data-collection techniques, models, and theories of science (*1*). Virtual experiments delivered with computer technology add value to physical experiments by allowing students to explore unobservable phenomena; link observable and unobservable phenomena; point out salient information; enable learners to conduct multiple experiments in a short amount of time; and provide online, adaptive guidance. Combinations of virtual and physical laboratories offer advantages that neither one can fully achieve by itself.

In addition to their virtues for promoting conceptual knowledge, virtual laboratories have additional advantages such as offering cost-effective alternatives to physical laboratories for topics such as DNA gel electrophoresis (*21*). They also give students the opportunity to use experimental systems that are beyond the reach of schools [as is illustrated for the air bags project (Fig. 2)] (*17*). In addition, they can enable students to investigate conjectures that are not possible in physical experiments by, for example, changing the magnetic field of the earth, varying accumulation of greenhouse gases, or studying the impact of extreme heart rate and blood pressure.

Virtual investigations can equal or exceed the impact of physical investigations on measures of conceptual understanding but the excitement of conducting hands-on experiments also deserves attention. Studies comparing virtual and physical experiments have primarily measured impacts on conceptual understanding of scientific phenomena and inquiry practices, but other outcomes, such as interest in science as a career, are worthy of investigation.

Research on virtual and physical laboratories calls for nuanced decision-making (*27*). Clearly, there are times when virtual investigations could be equal to or more effective than physical investigations and times when physical laboratories are most appropriate. Designers of instruction can improve outcomes by taking advantage of the affordances of each type of laboratory. However, design of guidance to ensure that students benefit from laboratories remains the most crucial variable in the success of science instruction (*35*). To design laboratories that take advantage of powerful guidance requires interdisciplinary teams involving domain experts, technologists, and learning scientists. Such teams typically refine their designs based on trials in instructional settings.

More opportunities to take advantage of virtual or online investigations arise regularly and deserve further study. For example, funding from the European Union is making data from facilities such as the CERN particle accelerator or the European Space Agency's satellites available for use in schools (*36*). In addition, new technologies are increasing access to remote laboratories [e.g., (*36*, *37*)], raising new questions for researchers.

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